Energy efficiency measurement procedure for gearboxes in their entire operating range

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***Abstract*—Over the last decade, forced regulations and a growing social awareness with respect to energy efficiency have resulted in a renewed interest in the research for high efficient electrical machines. When an electrical motor is coupled to a machine, in many cases a gearbox or belt transmission is used. Research shows a lack of information on energy efficiency of these components. In comparison to electrical motors and drives, there is very few regulation and if efficiency values can be found in catalogues, there is no regulated test procedure available to validate the data. As a result, the reliability of these efficiency values is unknown and comparison between manufacturers and technologies is impossible. In this paper a test bench is proposed to measure the energy efficiency of a gearbox with an accuracy up to 0.4%. The test bench is used to measure the efficiency of gearboxes in their entire speed and torque range. Contour maps are used to visualize these measurement results. Moreover, a measurement campaign using different gearboxes is carried out to compare the energy efficiency in the manufacturers catalogue and the measured efficiency.**

I. Introduction

Rising energy prices and awareness regarding environmental issues resulted in a growing research effort in energy efficiency of electrical drivetrains [1]. Both regulations and research concerning the energy efficiency of electrical motors are numerous [2]–[4]. In the large majority of the electrical drive trains, some sort of transmission is used to couple the electrical motor to the application. Therefore, the efficiency of the most used transmissions, being belts and gearboxes, should be known to assess the energy efficiency of a system. However, there are no standards so far concerning the energy efficiency and measurement procedures for these transmissions. Literature concerning the energy efficiency of gearboxes is limited to models describing the energy behavior of certain components of a gearbox such as gear pairs [5], [6] or the behavior of lubrication [7]. However, as emphasized by recent standards [8], [9] a total system approach is needed to maximize the overall efficieny. This means information on the efficiency of mechanical transmission components, such as gearboxes and belt drives, will be required to determine which drive train components could be improved in order to optimize the overall system efficiency.

Due to the lack of reliable information on energy efficiency of gearboxes, the need for a test bench and measurement procedure emerged. This paper discusses the test bench build for testing gearboxes up to 15kW in their entire working area and introduced in [10]. In section II the technical set-up is discussed. The accuracy of the measurements and the measurement set-up is examined in section III. To obtain reproducible and reliable results, a measurement procedure is proposed in IV. [10] thoroughly discribes the test bench but only a limited number of measurement results are mentioned. However in this paper, section V discribes the results of a measurement campaign, using the given test bench and design procedure, to compare the the energy efficiency mentioned in the catalogues with the measured values. Moreover, the variation of the energy efficiency in the entire operating range of a gearbox is discussed in section VI.

II. TEST BENCH CONSTRUCTION

One way to measure the efficiency of a gearbox is to drive it with an electrical motor on one side and load the gearbox with a motor on the other side (Fig. 1). For this so called back to back electrical method, the drive motor sets the speed while the load motor sets the torque and works as a generator. In this case two torque and speed measurements are necessary to determine the efficiency.

Usually a gearbox reduces the speed and enlarges the input torque. This means the load motor has to be able to deliver a large torque, which results in a motor with higher power range. To solve this problem a second gearbox can be implemented to reduce the torque. As a result the load and drive motor can be equally sized as shown in Fig. 2.

This input-output measurement method, used in this paper, is also proposed in de draft version of [9] where compliance of a Power Drive System can be tested in a similar manner. The method allows a large range in types and power for gearboxes to be tested. Also it will be possible to measure the efficiency at different speed and load setpoints in a flexible way. The accuracy of the efficiency determination depends on the speed and mainly on the torque measurement. Selection of these sensors will be important.

A lot of industrial gearboxes are used for conveyors and other applications in the lower power range. Therefore a 15kW, 4-pole induction motor was selected at drive and load side. 4-pole because the gearbox specifications, such as nominal loading, are commonly given in catalogs at 1400rpm [11]. However, usually these gearboxes can be used at speeds up to 2800rpm. With the 4 pole drive motor this can easily be reached when a frequency converter is used. To ensure that the chassis doesn't become too complex and heavy and therefore expensive, a maximum permissible torque of 1000Nm is chosen. To be able to load the gearbox at 1000Nm a torque reducer with a ratio of 10:1 is selected. Taking these parameters into account the range of gearboxes that can be tested is defined and presented in table I.

The nominal torque of a 15kW, 4-pole induction motor is about 100Nm. Given the maximum torque for the test bench of 1000Nm the ratio of a 15kW gearbox cannot be lower than 10. When the input speed doubles, the limiting factor is no longer the torque but the speed of the load motor. Finally, As a 0.12kW motor is approximately the lowest power range for 3-phase IM [12] this case is also depicted in table I.

The measurement principle is depicted in Fig. 3.The loading of the gearbox is realized by means of the reducer gearbox via an IM with regenerative VSD in field oriented torque control mode and speed feedback. The drive side VSD, also with speed feedback, drives the gearbox at desired speed. By connecting both VSD's via the DC-bus, the energy flows from generator to drive side and only the losses of the system have to be supplied from the grid.

The direct method is used to determine the overall efficiency. It requires accurate measurement of the mechanical in- and output power of the device under test. The torque is measured by means of dedicated "dual range" torque sensors with an accuracy of 0.1% full scale (f.s.) . At input side the maximum torque is 10Nm/100Nm and at output 100Nm/1000Nm. The speed is measured using an incremental encoder of 1024pulses/rev. at input side and at output side a 360pulses/rev. encoder, embedded in the torque sensor, is used. The ambient and gearbox temperature are measured and logged with calibrated thermocouples type K. Also the temperatures of the torque sensors are logged. The impact of temperature is explained further on in this paper.

The control of the test bench is done with an embedded dSPACE 1103 acquisition board in combination with Matlab Simulink and dSPACE ControlDesk. With this system the desired torque and speed setpoints are controlled and all the measured data is synchronized, captured and logged.

Industrial gearboxes come in many sizes and types. In contradiction to electrical motors there is no standardization in terms of shaft height, shaft diameter, mounting, ... [13]. Consequently the design of the test bench has to be very

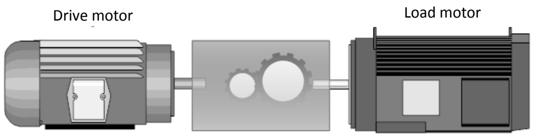


Fig. 1. Back-to-back electrical test setup

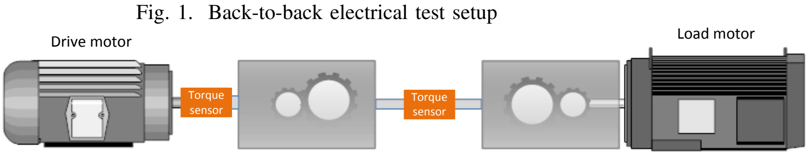


Fig. 2. Back-to-back electrical test setup with reducer

TABLE I

MEASURING RANGE TEST BENCH (**LIMITING VALUES IN BOLD**)

	Input Power P_{in} [kW]	Input Torque M_{in} [Nm]	Input Speed ω_{in} [rpm]	Max. ratio i	Output Torque M_{out} [Nm]	Output Speed ω_{out} [rpm]	Load Torque [Nm]	Load Speed [rpm]
Max. P	15	100	1460	10	**1000**	140	100	1460
	15	50	2920	10	500	292	50	**2920**
Min. P	0.12	0.78	1460	1282	**1000**	1.14	0.78	11.4
	0.12	0.39	2920	2564	**1000**	1.14	0.39	11.4

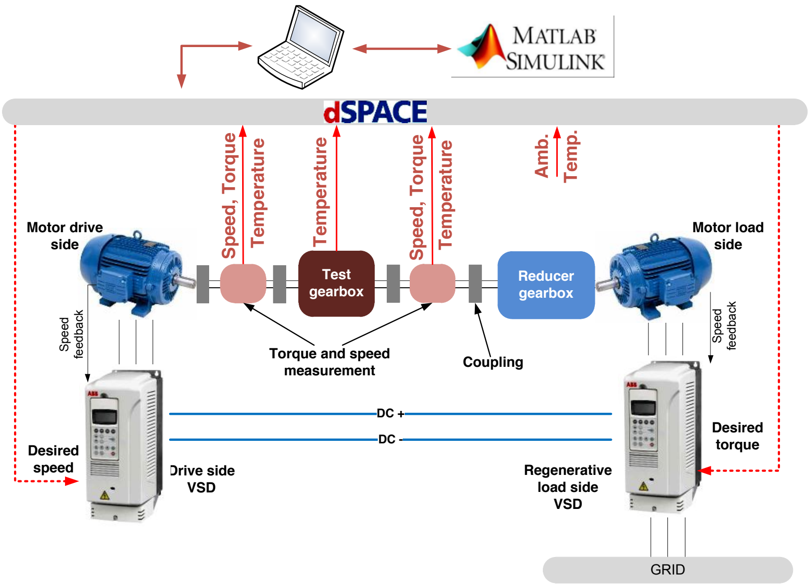


Fig. 3. Measurement principle gearbox test bench

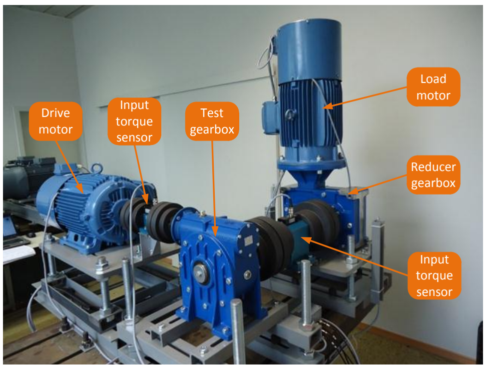


Fig. 4. Mechanical design gearbox test bench

flexible in order to test all types of gearboxes. As can be seen in Fig. 4 the height of the drive motor, load motor and test gearbox can be adjusted independently. The base plate of the gearbox under test is adjustable to allow different dimensions for fixation. In Fig. 4 the setup is made for an angled gearbox but the drive motor can rotate 90° to test straight gearboxes.

III. MEASUREMENT ACCURACY

The gearbox efficiency η_{gearbox} is determined by direct measurement of the mechanical input- and output power and can be calculated as follows:

$$\eta_{\text{gearbox}} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{M_{\text{out}}.\omega_{\text{out}}}{M_{\text{in}}.\omega_{\text{in}}} \tag{1}$$

Because of the mechanical design of the gears, the speed ratio i can be considered as constant [14]. In this research the speed ratio i mentioned in the catalogues are checked and confirmed by measurements. When the ratio is brought into the calculation, formula (1) evolves to:

$$i = \frac{\omega_{\text{in}}}{\omega_{\text{out}}} \quad \eta_{\text{gearbox}} = \frac{M_{\text{out}}}{M_{\text{in}}.i} \tag{2}$$

As a result the fault on the speed measurement doesn't affect the efficiency value if the exact ratio is known. The accuracy of the efficiency determination is then solely depending on the torque measurement at input and output. The two selected torque sensors [15] are equipped with strain gauges and have a contactless signal transmission from rotor to stator. The sensors have a dual torque range to benefit the accuracy at low torque measurement points. The torque sensor specs are listed in table II.

TABLE II
SPECIFICATIONS TORQUE SENSORS DR-2531 [15]

	Input Troque $M_{\mathbf{in}}$	Output Torque $M_{\mathbf{out}}$
Range	10Nm / 100Nm	100Nm / 1000 Nm
Accuracy	0.1% f.s.	0,1% f.s.
Speed Measurement	No	360 pulses/rev, 2xTTL
Output	±10V DC	±10V DC

The relative fault (RF) on the efficiency can be calculated by summing up the relative faults on the torque measurements:

$$RF_{\eta}(tot) = RF(M_{\mathbf{in}}) + RF(M_{\mathbf{out}}) \tag{3}$$

$$RF_{\eta}(tot) = \frac{AF(M_{\mathbf{in}})}{|M_{\mathbf{in}}|} + \frac{AF(M_{\mathbf{out}})}{|M_{\mathbf{out}}|} \tag{4}$$

The fault on the torque consists of three different parts. The torque signal itself has a fault of 0.1% f.s.. The analog voltage output signal which represents the torque is captured via an analog digital converter of the dSPACE acquisition board. Due to the 16 bits resolution of the A/D converter over a range of 20V (± 10V) this absolute fault (AF) is:

$$AF_{\text{resolution}} = \frac{20V}{2^{16}} = 0.3mV \tag{5}$$

The fault given by the manufacturer on the A/D conversion is 0,25%. This fault together with faults due to the cables and signal isolation are compensated by calibrating the acquisition system. A constant voltage fed to the system input and precisely measured with a voltage meter with an accuracy of 0,1%. The measured calibration values are compared and used to correct the output signal. Because of this calibration the fault is reduced from 0,25% to 0,1%.

The fault calculation can be illustrated by the following example. Measured input torque is 95Nm and output torque is 920Nm for a gearbox with ratio 10.

An absolute error of ± 0,4% is reached with a measurement point close to full range of the sensors. If the torque sensors only would have a single range and a point at low load would be taken, the fault will be much larger. This is shown in table III were an example is given for two different load points.

TABLE III
FAULT COMPARISON ONE RANGE VERSUS DUAL RANGE SENSOR ($i = 10$)

$M_{\text{in}} = 8Nm$ $M_{\mathbf{out}} = 76Nm$	Single range sensors	Dual range sensors
Total RF	5.2 %	0.52 %
Total AF	95%±4.9%	95%±0.5%
$M_{\text{in}} = 10.5Nm$ $M_{\mathbf{out}} = 100Nm$	Worst Case	
Total RF	4.0 %	4.0 %
Total AF	95.2%±3.8%	95.2%±3.8%

If the measured torques lie just beneath the low torque range the fault gets high when only a high range would be available. With the dual range sensor this is avoided. When a point just above the first range (10Nm resp. 100Nm) is taken, the fault will be at its highest. In table III one can see in worst case the absolute error on the test bench is about 3.8%.

Input torque sensor: Range 100Nm; 0.1% f.s.

$$AF(M_{\mathbf{in}}) = 100Nm.\frac{0.1}{100} = \pm 0.1Nm$$

A/D converter input signal: Range 10V; 0.1% f.s.

$$\begin{aligned} AF(AD_{\mathbf{in}}) &= 10.\frac{0.1}{100} = \pm 0.01V = \pm 10mV \\ 100Nm &\hat{=} 10V \\ AF(AD_{\mathbf{in}}) &= \pm 0.10Nm \end{aligned}$$

Resolution converter input signal:

$$\begin{aligned} 100Nm &\hat{=} 10V \\ AF(R_{\mathbf{out}}) &= 0.0003V.10Nm/V = 0.003Nm \end{aligned}$$

Output torque sensor: Range 1000Nm; 0.1% f.s.

$$AF(M_{\mathbf{out}}) = 1000Nm.\frac{0.1}{100} = \pm 1Nm$$

A/D converter input signal: Range 10V; 0.1% f.s.

$$\begin{aligned} AF(AD_{\mathbf{in}}) &= 10.\frac{0.1}{100} = \pm 0.01V = \pm 10mV \\ 100Nm &\hat{=} 10V \\ AF(AD_{\mathbf{out}}) &= \pm 1Nm \end{aligned}$$

Resolution converter output signal:

$$\begin{aligned} 1000Nm &\hat{=} 10V \\ AF(R_{\mathbf{out}}) &= 0.0003V.100Nm/V = 0.03Nm \end{aligned}$$

Fault on efficiency:

$$\begin{aligned} RF(\eta) &= \frac{AF(M_{\mathbf{in}}) + AF(AD_{\mathbf{in}}) + AF(R_{\mathbf{in}})}{|M_{\mathbf{in}}|} \\ &+ \frac{AF(M_{\mathbf{out}}) + AF(AD_{\mathbf{out}}) + AF(R_{\mathbf{out}})}{|M_{\mathbf{out}}|} \\ &= \frac{0.1 + 0.1 + 0.003}{95} + \frac{1 + 1 + 0.03}{920} \\ &= 0.00434 \end{aligned}$$

The efficiency based on the torque measurements:

$$\eta = \frac{M_{\text{out}}}{i.M_{\text{in}}} = \frac{920Nm}{95Nm.10} = 0.968$$

The absolute error is then:

$$AF(\eta) = |\eta|.RF(\eta) = 0.00420$$

$$\eta = 96.8\% \pm 0.4\%$$

Fig. 5 shows the ambient temperature influence on the efficiency. To measure this influence the gearbox was loaded with a contant nominal torque and driven at nominal speed. The tests show a significant efficiency difference when the ambient temperature varies. A temperature rise of 10°C results in an efficiency rise of ±2%. The temperature dependency is caused by several parameters such as oil temperature and viscosity [16], mounting position, oil level, mechanical properties and the temperature sensitivity of the torque sensors. To counteract the latter, a thermal model was made up. By measuring the temperature of the sensors at every measuring point, the model illustrated in Fig. 6 can be used to compensate this error. To make sure the test bench gives reproducible measurements it is important to stabilize the ambient temperature. Therefore the complete test set-up was placed in a temperature controlled room kept at 23°C.

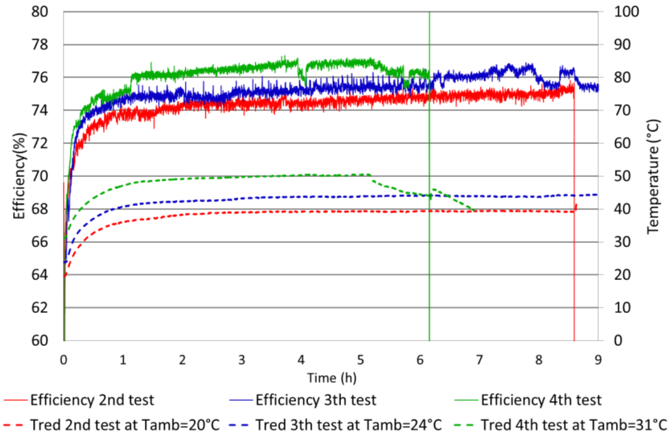


Fig. 5. Efficiency comparison at different ambient temperature

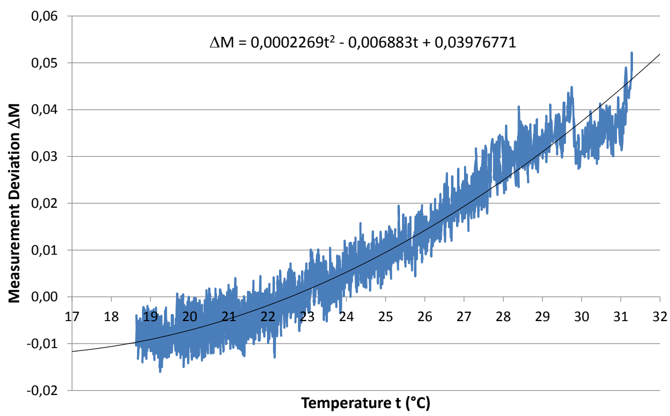


Fig. 6. Thermal model of the torque sensor

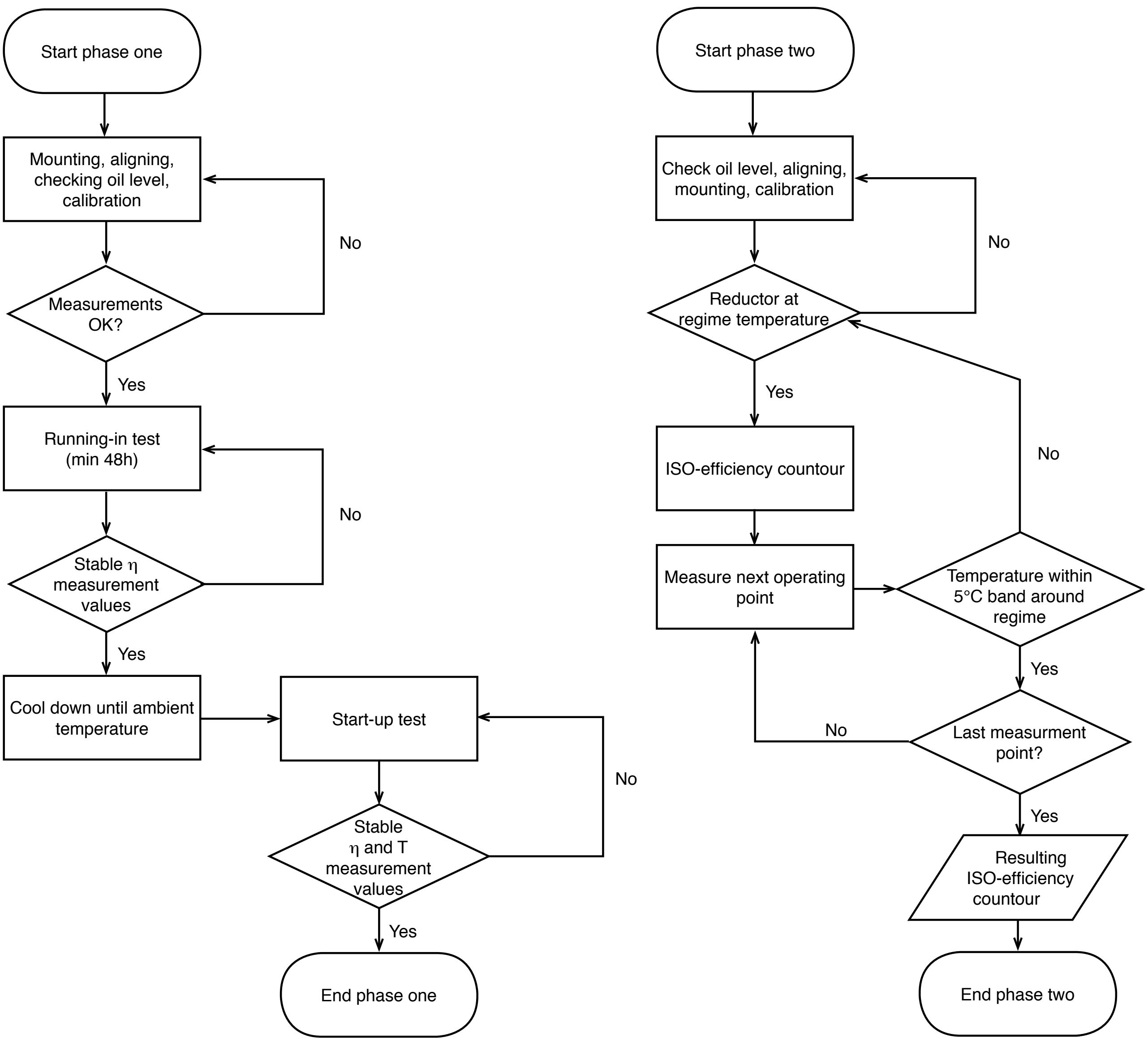


Fig. 7. Proposed measurement procedure

IV. Proposed measurement procedure

In order to guarantee reproducibility and obtain accurate measurements, a measurement protocol is proposed. First the gearbox under test first is fixed on the test bench and the gearbox input and output shaft are precisely aligned with respectively using a dedicated laser alignment [17]. The oil level has to be checked with the prescribed level in accordance with its the mounting position.

Before starting the actual efficiency measurements, the gearbox is subjected to a running-in test. In the first operating hours a gearbox doesn't work at its nominal efficiency. First the gears will run in and in this way "polish themselves". In the most gearbox catalogs this running-in is also stated and a running-in period of 24 to 48 hours is mentioned before nominal values are reached. To start up the running-in test the gearbox is driven and loaded at rated values for a minimum of 48 hours. After this period the measurement values, especially efficiency and gearbox temperature, are checked until they stabilize.

The second test is carried out to confirm the gearbox has run in and reproducible measurements can be obtained. After the running-in test the setup is disabled to cool down until ambient temperature. Then the setup is started up again at nominal load and speed. If constant gearbox temperature and efficiency are being reached the next step in the procedure can be taken. Otherwise, the start-up test is performed again from ambient temperature until reproducible results are obtained. Usually this start-up test takes about 1 to 2 hours depending on the size of the gearbox. The stabilized gearbox temperature will be used as reference temperature for the next experiments.

After these two tests the actual measurement phase can start as depicted in Fig. 7.

V. Comparison between catalogue reference values and measured energy efficiency

A first indication of a gearbox efficiency could be the values mentioned in the suppliers catalogue. However, as there is no standard procedure to determine this efficiency, every supplier could use their own method to measure or calculate this efficiency. A comparison between different brands based on the energy efficiency values provided by the suppliers is very difficult. To prove this statement, the method proposed in this paper is used to determine the energy efficiency of 13 gearboxes of 6 different brands at nominal load an speed. Concerning the orientation of the input and output axis both right angled (⊥) and a straight (-) type is measured. Moreover, 5 different technologies are included being: Worm (W), Helical Bevel (HB), Helical Worm (HW), Helical Spirod (HS) and Helical (H), all illustrated in table IV. Table V shows the lack of clear standardization results in large deviations between the measured energy efficiency and the catalogue values. Only three measured energy efficiency values are higher compared to the one mentioned in the catalogue while for all other gearboxes the opposite is true. While brand E provides quite exact efficiency values, other brands clearly use less accurate methods to determine the energy efficiency. Table V supports the conclusion that efficiency comparison between gearboxes of different suppliers based on their catalogues is impractical.

VI. Trends in the entire operating range

The depicted values for measured efficiency in table V are measured at nominal load and speed. However, as drivetrains are often over dimensioned or operated at different loads and speed setpoints, the energy efficiency in the entire operating range of the machine is of interest. Therefore the efficiency of the Helical Bevel gearbox of brand D and the Helical gearbox of brand E is measured at 16 different torque values and 19 speed measurement points. In this way, iso efficiency maps [18], [19] are obtained for both gearboxes. The measurement results depicted in Figs. 8 and 9, show the optimal energy efficiency is only obtained at nominal load. While the speed setpoint has very little impact on the energy efficiency the efficiency and the load have a proportional relation.

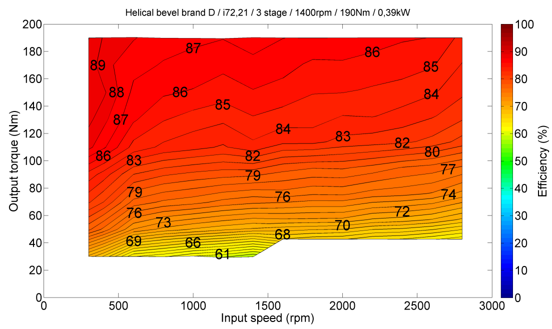


Fig. 8. iso efficiency map Helical Bevel

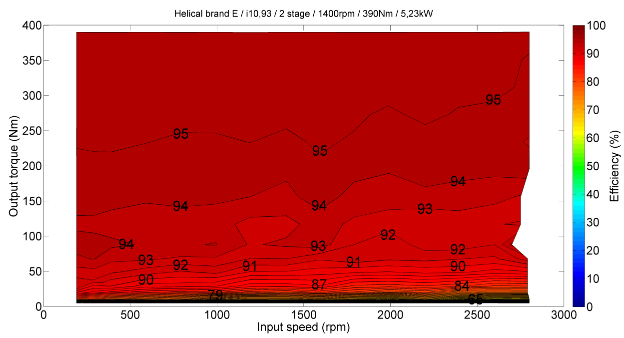


Fig. 9. iso efficiency map Helical

VII. Conclusion

Where both literature and standards lack the description of a standard procedure to measure the energy efficiency of a gearbox this paper proposes a method to measure the energy

TABLE IV

GEARBOX TECHNOLOGIES

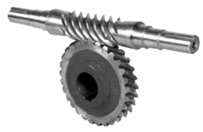
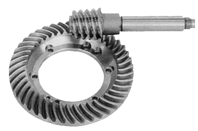
Worm (W)	Helical (H)	Helical Bevel (HB)	Helical Worm (HW)	Helical Spirod (HS)
		 + 	 + 	 + 

TABLE V

COMPARISON BETWEEN CATALOGUE REFERENCE VALUES AND MEASURED ENERGY EFFICIENCY

	Brand A	Brand B	Brand C			Brand D		Brand E			Brand F		
Type	⊥	⊥	⊥	⊥	⊥	⊥	⊥	⊥	⊥	-	⊥	⊥	⊥
Technology	W	HB	HB	HW	HS	HB	HW	HB	HW	H	HW	HW	HW
Stages	1	2	3	2	2	3	2	3	2	2	2	2	2
Ratio i	80	77.76	72.54	71.75	74.98	72.21	77	11.41	11.67	10.93	87.65	68.44	30.26
Torque [Nm]	450	505	186	167	180	190	180	434	373	390	285	270	260
Power [kW]	0.82	0.95	0.37	0.35	0.36	0.39	0.34	5.58	4.7	5.23	0.69	0.82	1.51
Catalog Efficiency [%]	62	95	96	62	90	95	78	94	90	96	69	71	83
Measured Efficiency [%]	73	84.5	88	56.5	65.5	87.5	70.5	95.5	91.5	95.5	60	61	68
Δ Catalog - Measured [%]	-11	10.5	8	5.5	24.5	7.5	7.5	-1.5	-1.5	0.5	9	10	15

efficiency of such a transmission in its entire operating range. The paper describes this method and a measurement accuracy is discussed. Based on the comparison of the measured energy efficiency with the values mentioned in catalogues one can conclude a standard procedure is necessary to compare the values provided by the suppliers of gearboxes. Moreover, iso efficiency maps reveal the energy efficiency rises when a gearbox is loaded with higher torques.

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